Ocean Surface Wind Direction Measurement by Scanning Polarimetric Microwave Radiometry

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Abstract — The retrieval of ocean surface wind vector from polarimetric microwave brightness temperature fields is posed as a nonlinear inversion of the geophysical model function (GMF) for emission using maximum likelihood (ML) estimation. Applying the maximum likelihood estimator results in a weighted least-squares minimization problem that is valid for multi-look, multi-frequency, multi-polarization microwave brightness temperature measurements. By coupling this result with an empirically derived GMF, wind direction retrieval is demonstrated using multi-band conically-scanned polarimetric microwave brightness imagery obtained using the Polarimetric Scanning Radiometer (PSR) during observations over the Labrador Sea in March 1997.

INTRODUCTION

Boundary layer winds drive the ocean surface creating gravity and capillary waves which in turn cause azimuthal dependences in the upwelling microwave brightness temperatures [1, 2]. This dependence has been observed using both satellite [3] and aircraft radiometers [4, 5, 6] in all four components of the Stokes vector [7]. The object of this study is to exploit this observed dependence for the purpose of retrieving the ocean surface wind direction from measured polarimetric brightness temperatures.

Wind direction retrieval using both airborne and spaceborne scatterometers has been well studied [8]. The problem of wind direction retrieval from polarimetric microwave radiometers, however, has to date been less thoroughly addressed. In this paper a multi-look wind direction retrieval method is presented using maximum likelihood (ML) estimation theory. The problem is posed in

a form allowing an arbitrary set of azimuth look angles, frequency bands, and polarization states. The result is a non-linear weighted least-squares minimization problem which may be solved using any of several multivariate search tools. The utility of the multi-look wind direction retrieval technique is demonstrated using conically-scanned polarimetric microwave brightness imagery obtained using the Polarimetric Scanning Radiometer (PSR) during aircraft observations over the Labrador Sea in March 1997 [5].

PSR DATA SET

The Polarimetric Scanning Radiometer (PSR) [9] is the first multi-channel tri-polarimetric (first three Stokes parameters) high-resolution imaging radiometer for aircraft-based studies of land and ocean emission. The PSR is a conical scanning radiometer designed to measure the first three Stokes parameters (T_v, T_h, and T_U) at 10.7, 18.7, 37.0, and 89.0 GHz. In March 1997, the PSR, along with a complement of passive and active instruments (together known as the Ocean Winds Imaging suite, or OWI [5]), was operated aboard the NASA Wallops Flight Facility P-3B as part of the Labrador Sea Deep Convection Experiment. Conically-scanned microwave brightness imagery of the wind driven ocean surface was collected during coordinated flights over the *R. V. Knorr*. PSR data collected on March 4, 1997 from 15:00-16:00 UTC were chosen to develop an ocean wind GMF for this study. Centered over the *Knorr*, the flight pattern consisted of six straight and level flight legs organized in three pairs, each 60° apart in heading. This "hex-cross" pattern covered triangular area ~30 km along a side (Fig. 1). Data collected during the pattern consisted of 135 scans with 227 samples per scan at an elevation angle of 53.1°. Surface winds were ~14 m/s from ~260° as measured by both GPS dropsonde and *Knorr* wind sensors. The ocean temperature measured at $h = -3$ m was 3°C and the air temperature at $h = 23$ m was -12°C, thus, the air-sea temperature
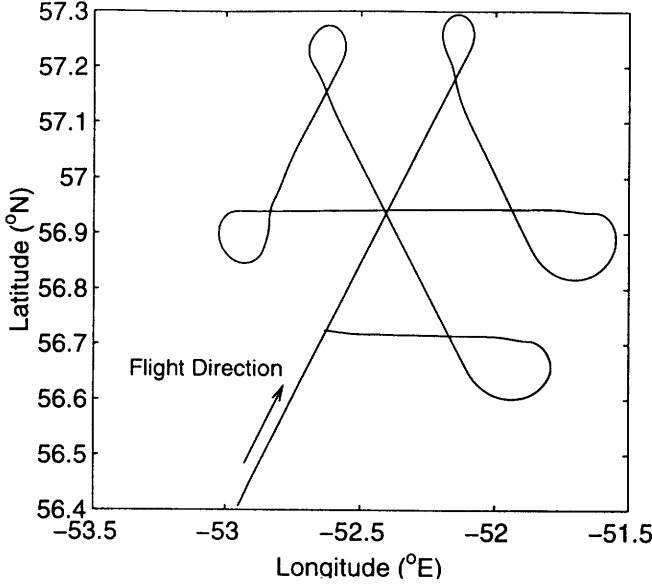
Figure 1: Hex-cross flight pattern used for PSR observations of ocean winds on March 4, 1997.

difference of 15°C indicated significant boundary layer instability.

GMF FOR WIND DIRECTION HARMONICS

The mean azimuthal brightness variations over a wind driven ocean are well characterized using a second-order harmonic expansion [3]. Using the above data set, the first- and second-order harmonic amplitudes were determined via a least-squares fit to the mean azimuthal signature. The mean azimuthal brightness signatures and harmonic approximations are shown in Fig. 2. As illustrated by the error curves, radiometric noise and brightness temperature variability of geophysical origin influenced the variances of the harmonic amplitude measurements. For comparison, the 37 GHz SSM/I global average wind direction harmonics from [3] are also plotted. Because the SSM/I 19 GHz and 37 GHz signatures are similar and the SSM/I does not provide 10 GHz measurements, the 37 GHz SSM/I harmonic function is used for comparison at all three frequencies.

The plots show a distinct variation of 2-4 K with strong first and second harmonic dependence in the vertical and horizontal polarziations, respectively. For both polarizations, the dominant harmonic amplitude increases with increasing frequency. Furthermore, the measured vertical and horizontal harmonic amplitudes at 18.7 GHz and 37.0 GHz exhibit excellent agreement with the SSM/I global average wind direction harmonics. Although slightly lower in amplitude, the PSR 10.7 GHz wind direction har-

monics are otherwise comparable to the 37 GHz SSM/I harmonics.

Of particular interest is the strong ($\sim$1 K amplitude) first harmonic present in the third Stokes parameter signature. The large first harmonic content of this signature is indicative of a strong windward-leeward asymmetry in the ocean wave structure. The measurements are similar to simulated results obtained using an asymmetric wave geometrical optics model [1].

ML ESTIMATION OF WIND DIRECTION

The upwelling brightness temperatures over the ocean are related to several influential geophysical parameters (wind speed and direction, wind stress, stability, foam coverage, fetch) by the GMF. The brightness temperature output from a radiometer is equal to the GMF evaluated for the specific ocean state plus instrument noise and any geophyiscal modelling error. If the noise and modelling errors are assumed to be Gaussian, the measured brightness temperature vector $\widehat{\overline{T}}_B$ for a multi-frequency polarimetric radiometer with n channels is modelled as an $n \times 1$ random vector that follows the n-dimensional joint Gaussian probability density function (pdf):

$$f\left(\widehat{\overline{T}}_B\right) = \frac{1}{(2\pi)^{n/2} \left[\det\left(\overline{\overline{K}}\right)\right]^{1/2}} \times$$
$$\exp\left[-\frac{1}{2}\left(\widehat{\overline{T}}_B - \overline{T}_B\right)^T \overline{\overline{K}}^{-1} \left(\widehat{\overline{T}}_B - \overline{T}_B\right)\right], \quad (1)$$

where

$$\mathrm{E}\left[\widehat{\overline{T}}_B\right] = \overline{T}_B = (T_1, T_2, \cdots, T_n)^T$$

$$\overline{\overline{K}} = \begin{bmatrix} \Delta T_1^2 & & 0 \\ & \ddots & \\ 0 & & \Delta T_n^2 \end{bmatrix}$$

$$\det\left(\overline{\overline{K}}\right) = \prod_{i=1}^{n} \Delta T_i^2.$$

The mean $\overline{T}_B$ is the expected value of the brightness vector as determined by the multidimensional GMF for the appropriate ocean state. The individual ΔT_n within the covariance matrix $\overline{\overline{K}}$ are the rms deviations due to the combined effects of instrument noise and geophyiscal modelling uncertainty. For M independent looks (e.g., at different azimuth angles), the joint pdf of the observed brightness temperatures is simply the product of the respective pdf's (1) for each of the M looks

$$f\left(\widehat{\overline{T}}_{B,1}, \cdots, \widehat{\overline{T}}_{B,M}\right) = \prod_{m=1}^{M} f\left(\widehat{\overline{T}}_{B,m}\right).$$

Vertical Polarization — **Horizontal Polarization** — **Third Stokes Parameter**

10.7 GHz, ΔT (K): $a_1 = 0.90 \pm 0.3$ K, $a_2 = 0.09 \pm 0.3$ K; $\Delta T_{rms} = 0.14$ K

Horizontal 10.7 GHz: $a_1 = 0.18 \pm 0.4$ K, $a_2 = 1.00 \pm 0.3$ K; $\Delta T_{rms} = 0.17$ K

Third Stokes 10.7 GHz: $b_1 = 0.71 \pm 0.4$ K, $b_2 = 0.69 \pm 0.3$ K; $\Delta T_{rms} = 0.20$ K

18.7 GHz, ΔT (K): $a_1 = 1.44 \pm 0.4$ K, $a_2 = 0.18 \pm 0.4$ K; $\Delta T_{rms} = 0.23$ K

Horizontal 18.7 GHz: $a_1 = 0.32 \pm 0.4$ K, $a_2 = 1.08 \pm 0.5$ K; $\Delta T_{rms} = 0.25$ K

37.0 GHz, ΔT (K): $a_1 = 1.62 \pm 0.3$ K, $a_2 = 0.12 \pm 0.3$ K; $\Delta T_{rms} = 0.12$ K

Horizontal 37.0 GHz: $a_1 = 0.34 \pm 0.4$ K, $a_2 = 1.32 \pm 0.5$ K; $\Delta T_{rms} = 0.40$ K

Third Stokes 37.0 GHz: $b_1 = 1.18 \pm 0.5$ K, $b_2 = 0.60 \pm 0.4$ K; $\Delta T_{rms} = 0.12$ K
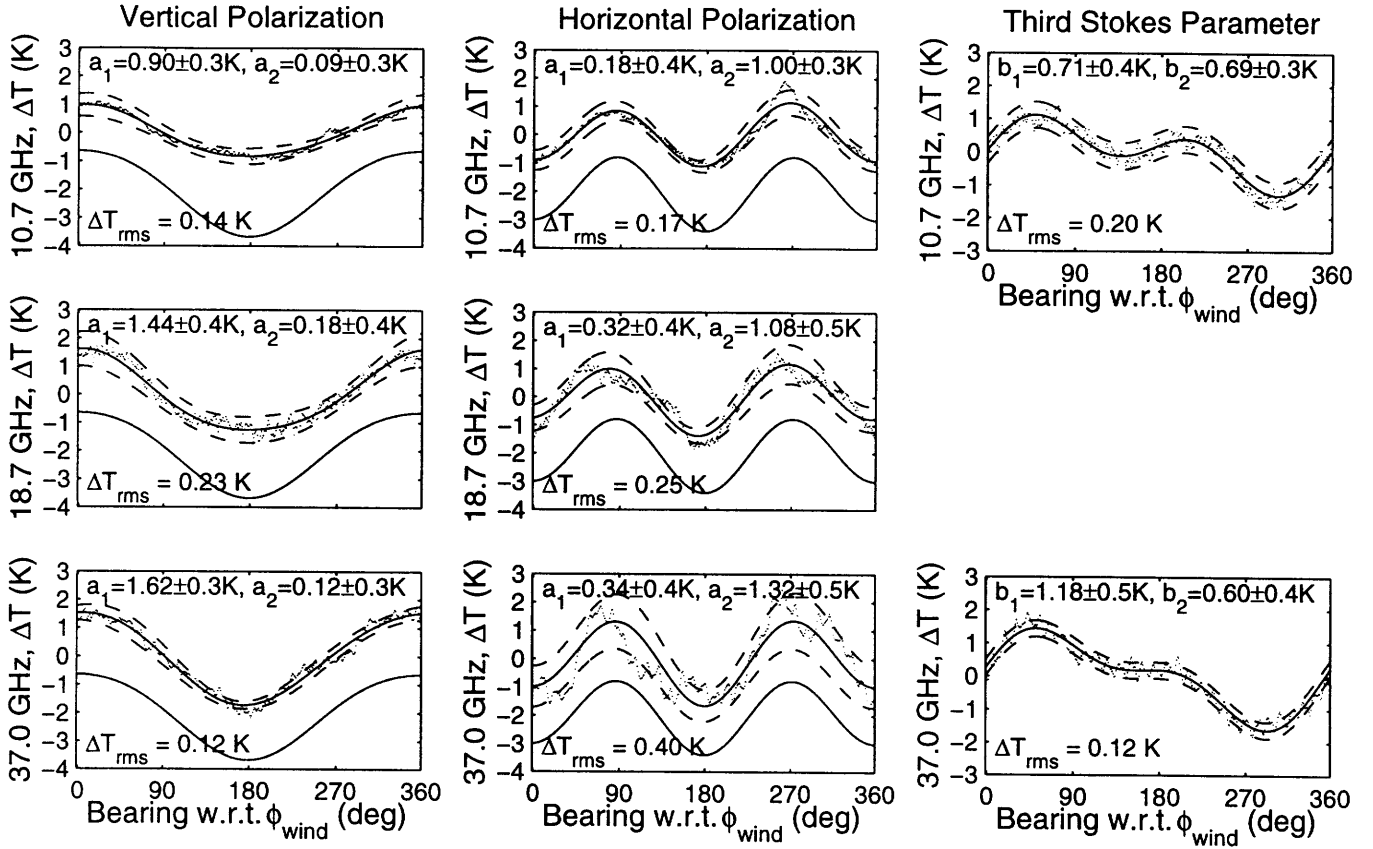
Bearing w.r.t. ϕ_{wind} (deg)

Figure 2: PSR azimuthal harmonics exhibiting wind direction dependence of the first three Stokes parameters at 10.7, 18.7, and 37.0 GHz. Data for T_U at 18.7 GHz was unavailable. The solid lines represent the reconstructed second-order harmonic expansions and the dashed lines are the $\pm 1\sigma$ error curves for 135 scans. Individual points indicate mean measured brightness deviations. The 37.0 GHz SSM/I global average wind direction harmonics, denoted by solid lines, are shifted by -2 K for clarity.

Given measurements from M looks we can determine the wind direction ϕ_w using the maximum likelihood (ML) technique. Following [10], the joint pdf of the M independent looks can be written $f\left(\widehat{\overline{T}}_{B,1}, \cdots, \widehat{\overline{T}}_{B,M}; \overline{W}\right)$, where $\overline{W} = [\langle \overline{T}_B \rangle^T, \phi_w]$. The components of $\overline{W}$ are the wind direction ϕ_w and the mean azimuthal brightness temperatures $\langle \overline{T}_B \rangle$, where $\langle \cdot \rangle$ is an average over all azimuth angles. These components are assumed to be constant but unknown. The ML estimator $\widehat{\overline{W}}_0$ of $\overline{W}$ is that value of $\widehat{\overline{W}}_0$ that maximizes the log likelihood function:

$$\ln L = -M \ln\left((2\pi)^{n/2} \left[\det\left(\overline{\overline{K}}\right)\right]^{1/2}\right)$$
$$- \frac{1}{2} \sum_{m=1}^{M} \left(\widehat{\overline{T}}_{B,m} - \overline{T}_{B,m}\right)^T \overline{\overline{K}}^{-1} \left(\widehat{\overline{T}}_{B,m} - \overline{T}_{B,m}\right).$$

The following is the equivalent objective function for what is now a minimization problem:

$$\sum_{m=1}^{M} \left(\widehat{\overline{T}}_{B,m} - \overline{T}_{B,m}\right)^T \overline{\overline{K}}^{-1} \left(\widehat{\overline{T}}_{B,m} - \overline{T}_{B,m}\right).$$

If $\overline{\overline{K}}^{-1}$ is diagonal as is assumed above, then this becomes the simple expression

$$\sum_{m=1}^{M} \sum_{i=1}^{n} \left(\widehat{T}_{i,m} - T_{i,m}\right)^2 \Delta T_i^{-2} \qquad (2)$$

where the subscript (i, m) denotes the i-th channel of the m-th look. This result is in the form of a non-linear weighted least-squares minimization problem with preference given to the less noisy channels.

RESULTS

To test the ML wind direction retrieval algorithm, PSR data from a flight on March 3, 1997 were chosen. The sur-
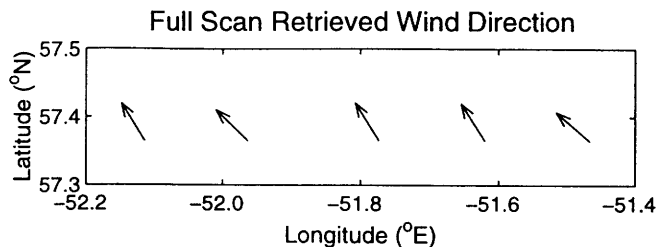
Full Scan Retrieved Wind Direction

Figure 3: Retrieval of sub-track wind direction using entire azimuthal scans of multi-band polarimetric brightness temperatures. The arrows indicate the upwind direction. The mean retrieved wind direction is $322° \pm 9°$.

face conditions were similar to those of the March 4, 1997 data set described above with winds at ~17 m/s from 319° (according to a GPS drop-sonde) or 14 m/s from 330° according to the *Knorr* observations. The test set consisted of 25 scans of 227 points each along a flight line. To reduce the radiometric noise and to smooth over geophysical variations, a moving average filter with width of five was applied to yield five independant averaged scans. The resulting sub-track wind direction estimates were plotted as upwind pointing arrows in Fig. 3. The mean retrieved wind direction was 322° with a standard deviation of 9°, thus indicating excellent agreement with the surface truth.

SUMMARY

A versatile retrieval algorithm based on the ML method was developed for infering the ocean surface wind direction from multi-look, multi-frequency, multi-polarization microwave brightness temperature measurements. The utility of this technique was demonstrated for the first time using multi-band polarimetric conically-scanned microwave brightness imagery. The above development and demonstration of the ML wind direction retrieval supports the case for continued development of a satellite based microwave radiometer wind vector sensor. An investigation of the performance of this algorithm in a simulated two-look satellite system and its robustness with respect to receiver noise, clouds, channel reductions, spot-size, and air-sea stability is underway.

ACKNOWLEDGMENTS

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